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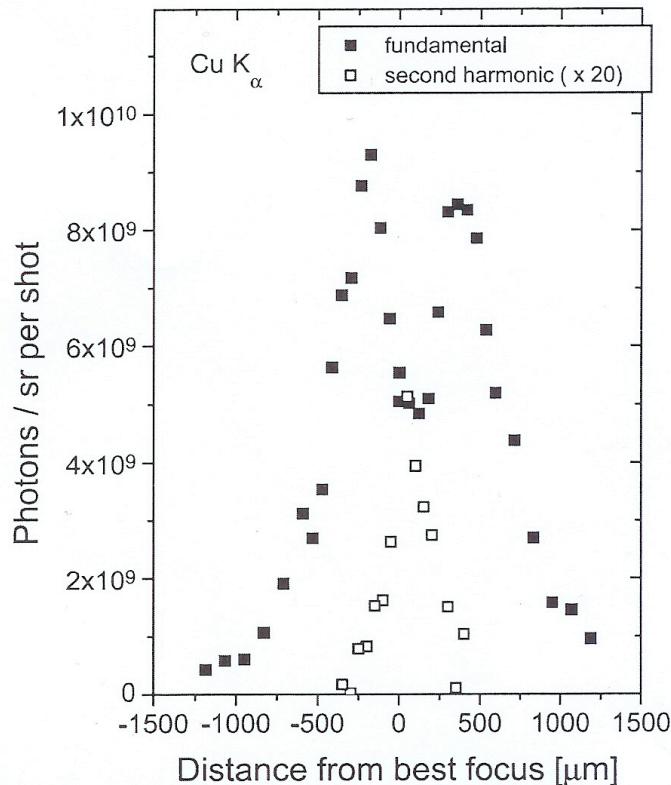
Femtosecond X-ray diffraction of coherent phonons in nanostructured semiconductors

- Femtosecond hard X-ray plasma source
- Intro: Semiconductor superlattice structures
- fs-XRD of phonons in heterostructures

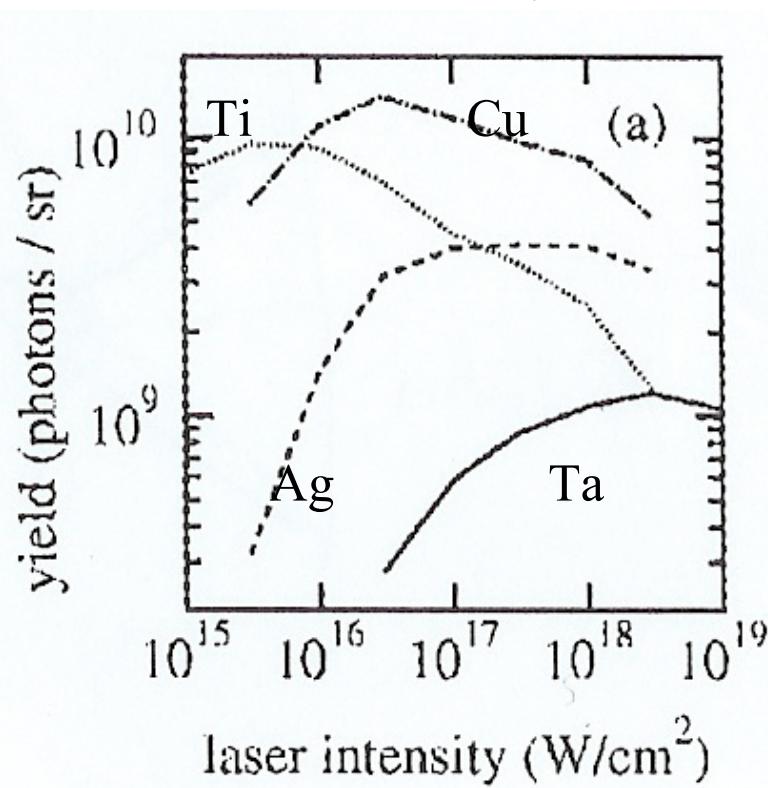
Fs-Laser-Plasma-Interaction: Experiment and Theory

- K_{α} yield as function of intensity for constant flux

10 Hz laser experiment: 200 fs, 200 mJ



PIC Simulation: 60 fs, 100 mJ

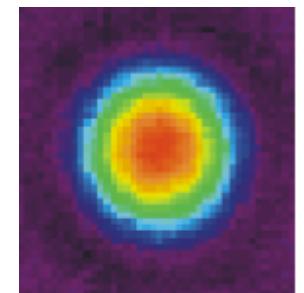
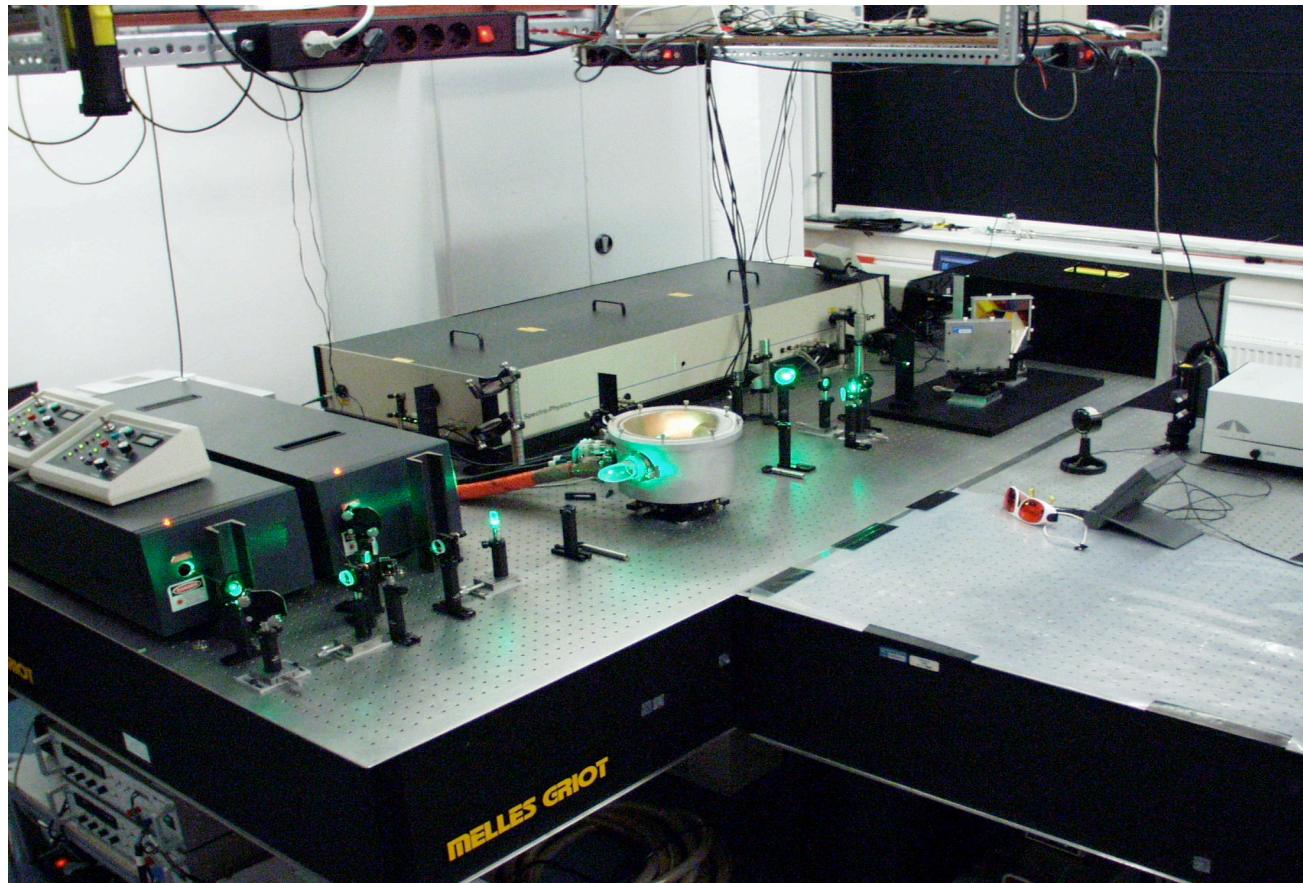


Laser System

Compressed: 7.5 W, 45 fs, 800 nm, 1 kHz

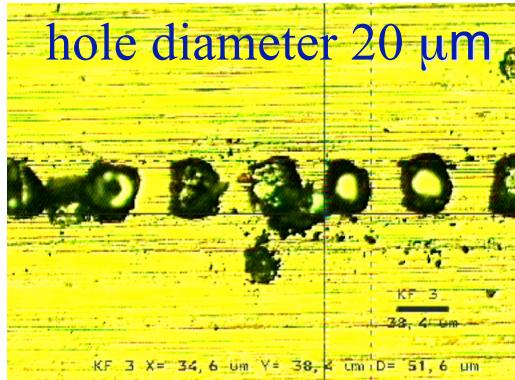
Actually used: 6.5 W compressed,

On target: 5 W, focus 8 μ m $\Rightarrow I = 2 \cdot 10^{17}$ W/cm²

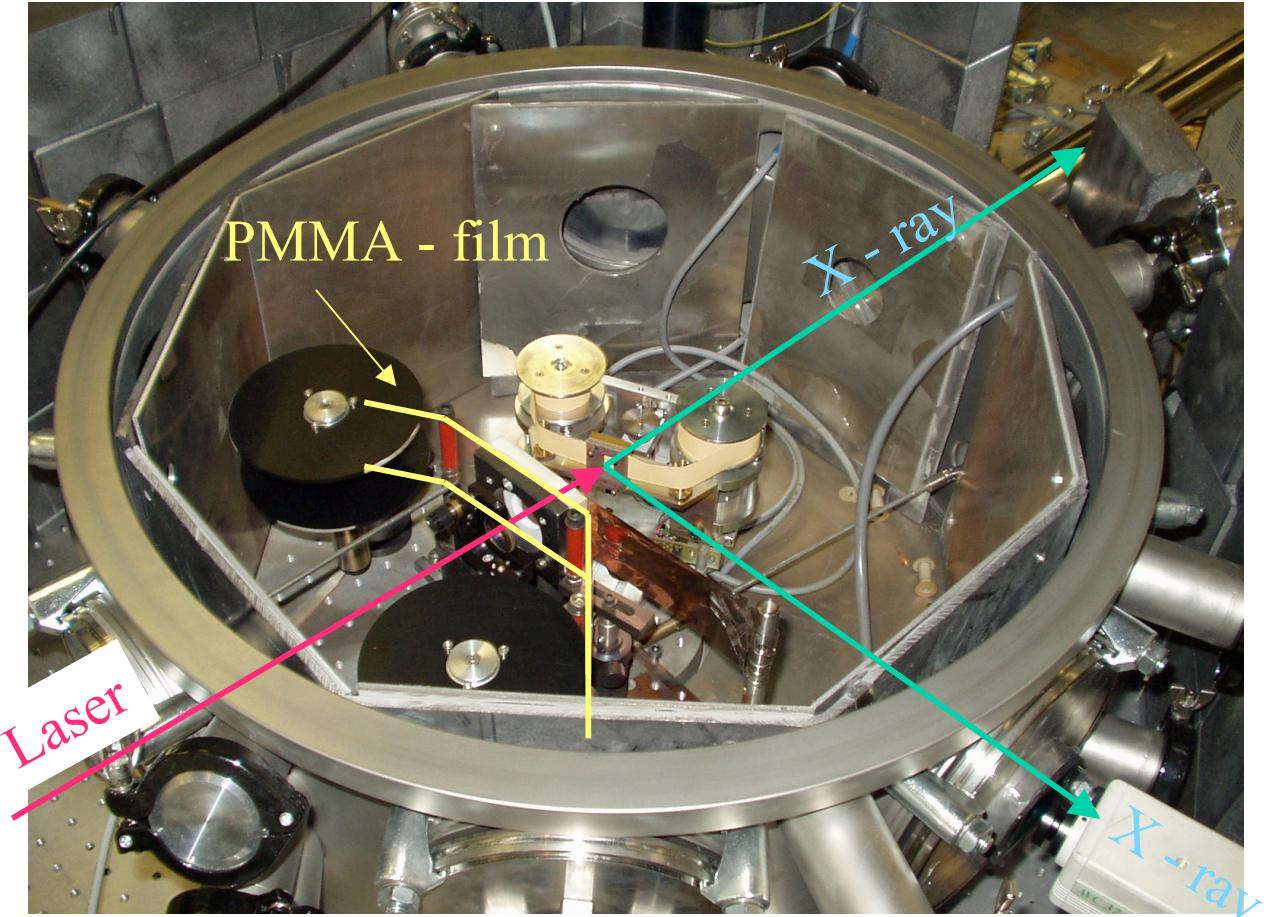


Copper - X-ray Plasma Source

- Plasma generated in vacuum
- Debris on laser-side moving PMMA film
- Debris on X-ray side plastic coated Cu-film



- Yield:
 $3.9 \times 10^{10} K_{\alpha} / (4\pi s)$



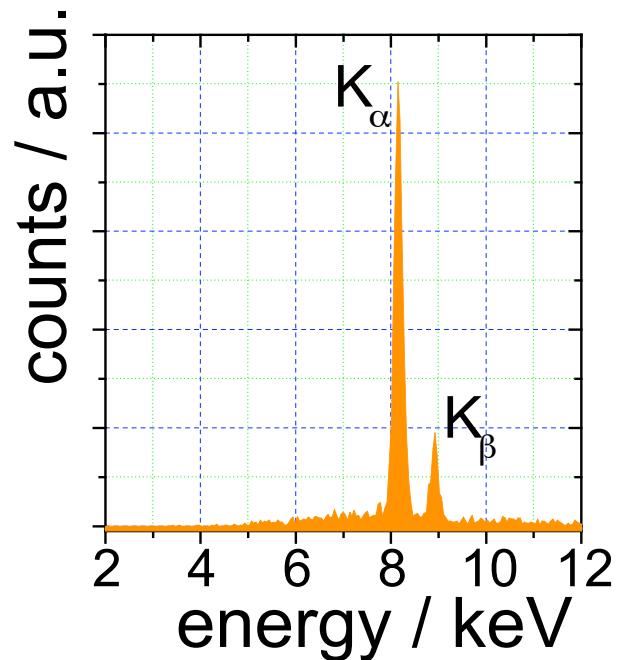
Parameters of Plasma Source

K_{α} line radiation:

	K_{α} energy / eV	K_{α} flux / $4\pi^*s$
Ga	9.2	4.5×10^{10}
Cu	8.2	3.9×10^{10}
Ni	7.5	6.7×10^{10}

- Plasma generated in 15 μm copper
- X-ray focus 15 μm
- Estimated pulse duration: 200 fs

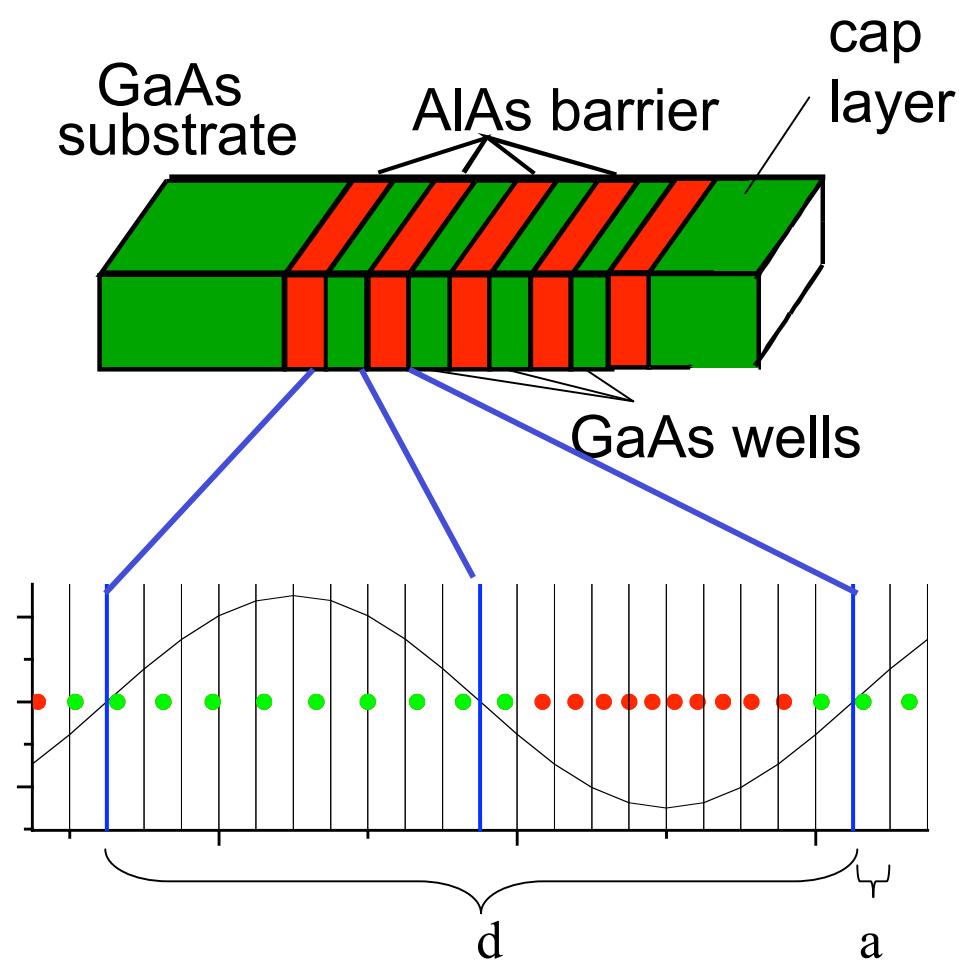
$$\text{Brilliance} = 4 \times 10^7 / (\text{mrad}^2 * \text{mm}^2 \text{s} * 0.1\% \text{BW})$$



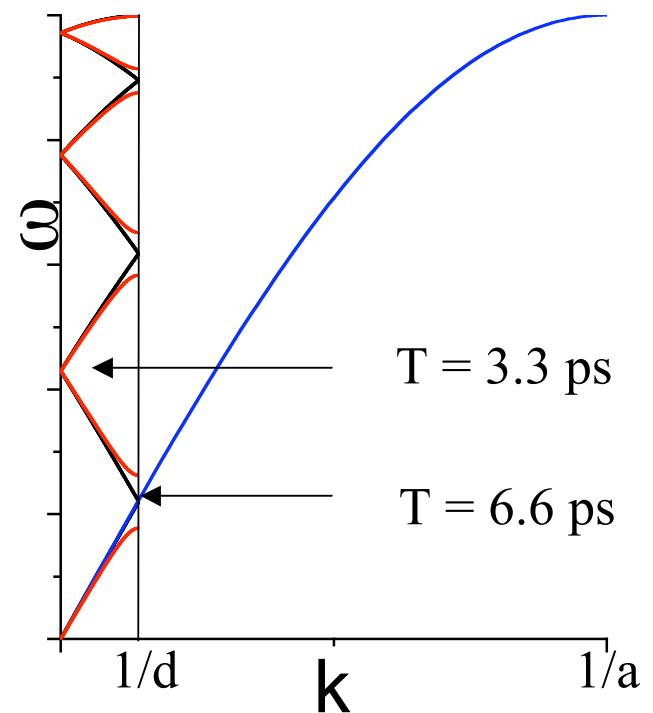
According to specs	Flux on sample / s	Focus / μm
Multilayer mirror (Osmic)	1.4×10^6	30
HOPG reflector (IfG)	5×10^7	200

Zone-Folded Longitudinal Acoustic Phonons

Superlattice:



Dispersion:



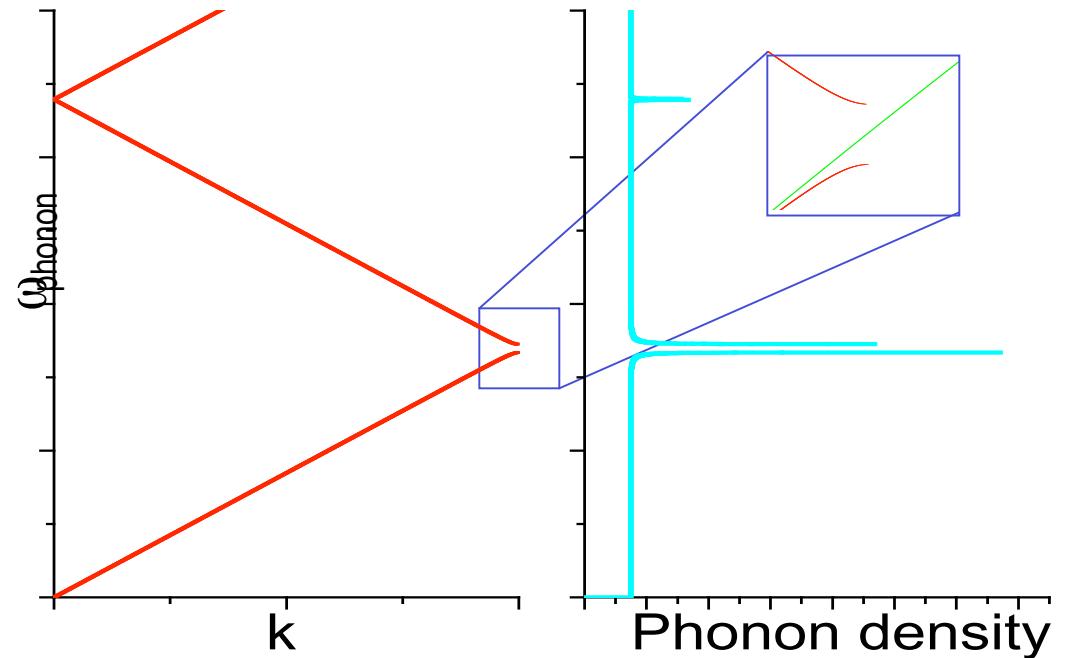
Our case: 8 nm / 8 nm

GaAs/Al_{0.4}Ga_{0.6}As

Superlattice with Cap-Layer

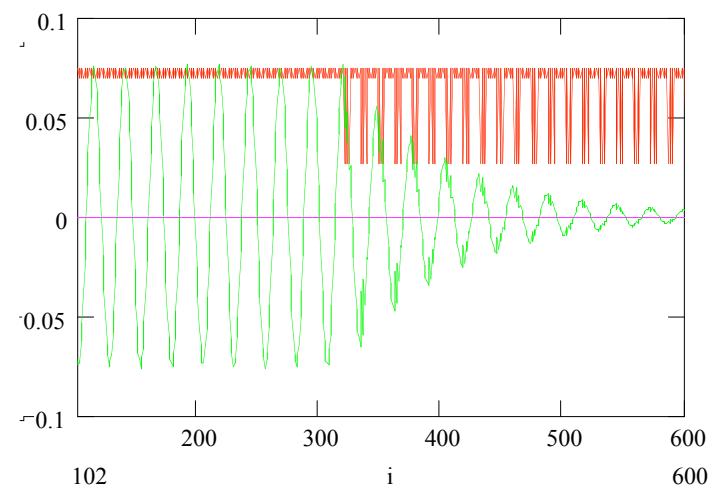
Infinite superlattice:

- Phononic crystal: band gap reflects phonons @ ω_{gap}
- High density of states at zone boundary
- Engineering of band-gaps



With cap layer

- Phonon states within bandgap of SL
- Confined phonons



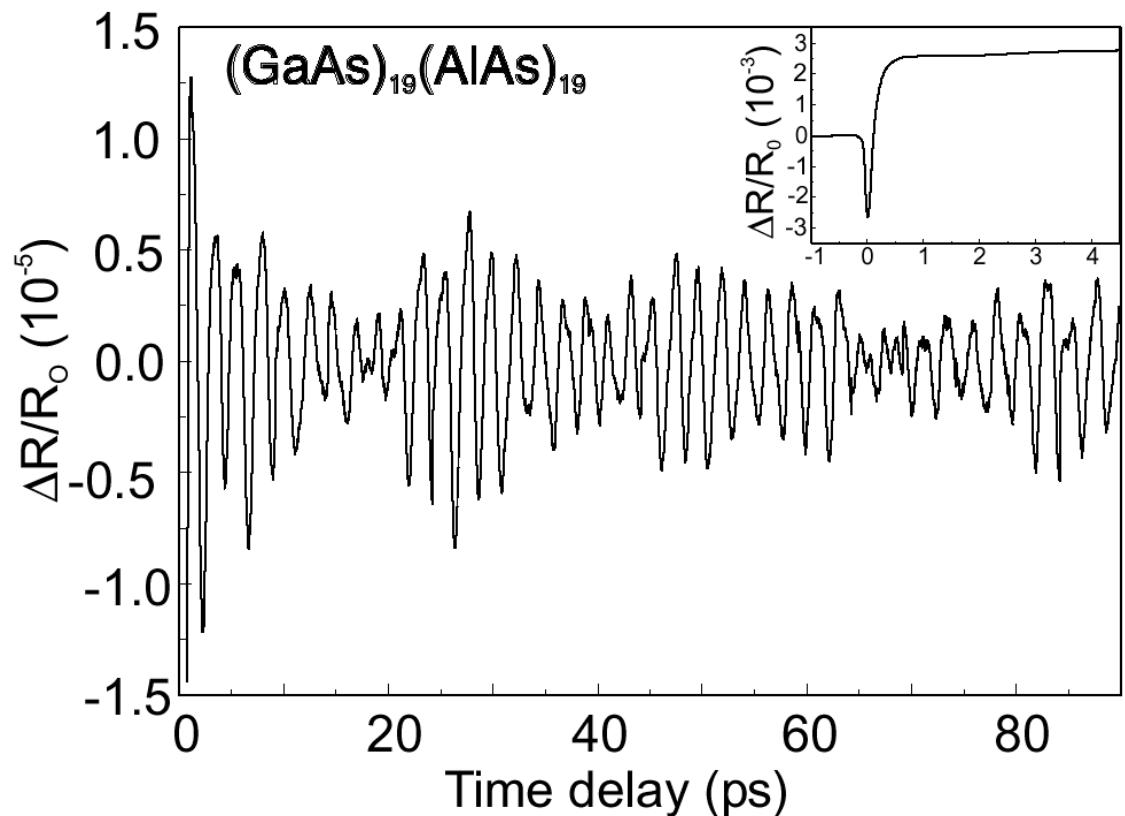
Time-resolved Optical Reflection

800 nm pump
800 nm probe

Folded phonon at $k = 0$
(would be 3.3 ps)

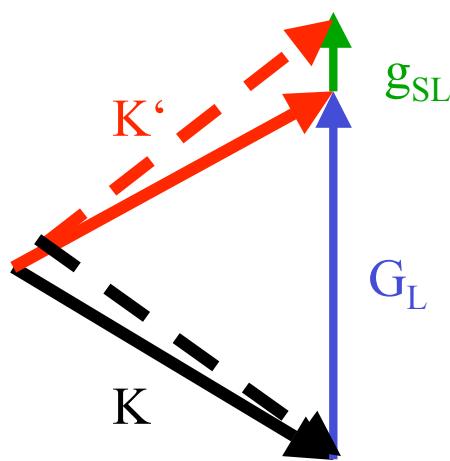
Limitation:

- Creation of electron hole plasma
- Only weak excitation with oscillator pulses
- No buried structures

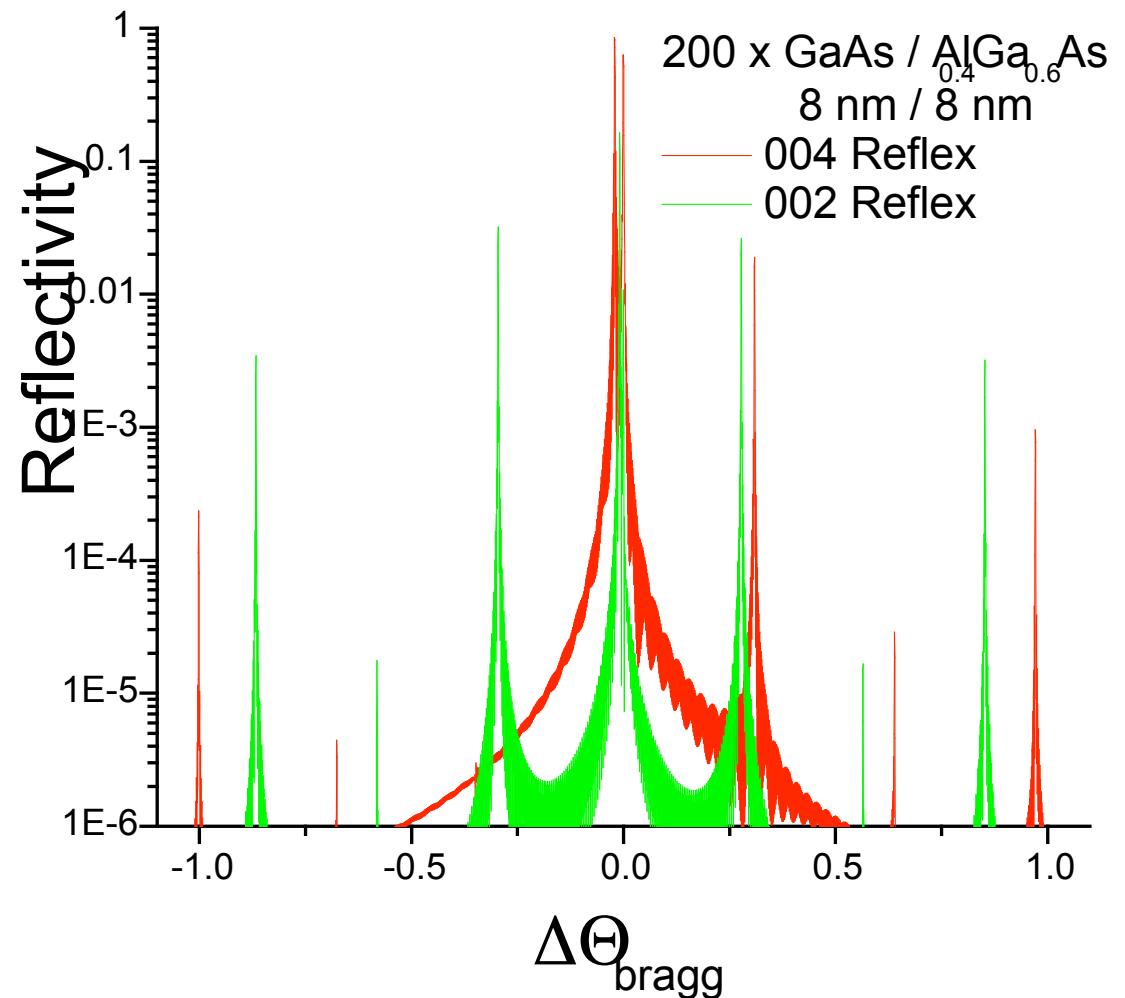


XRD of Superlattices

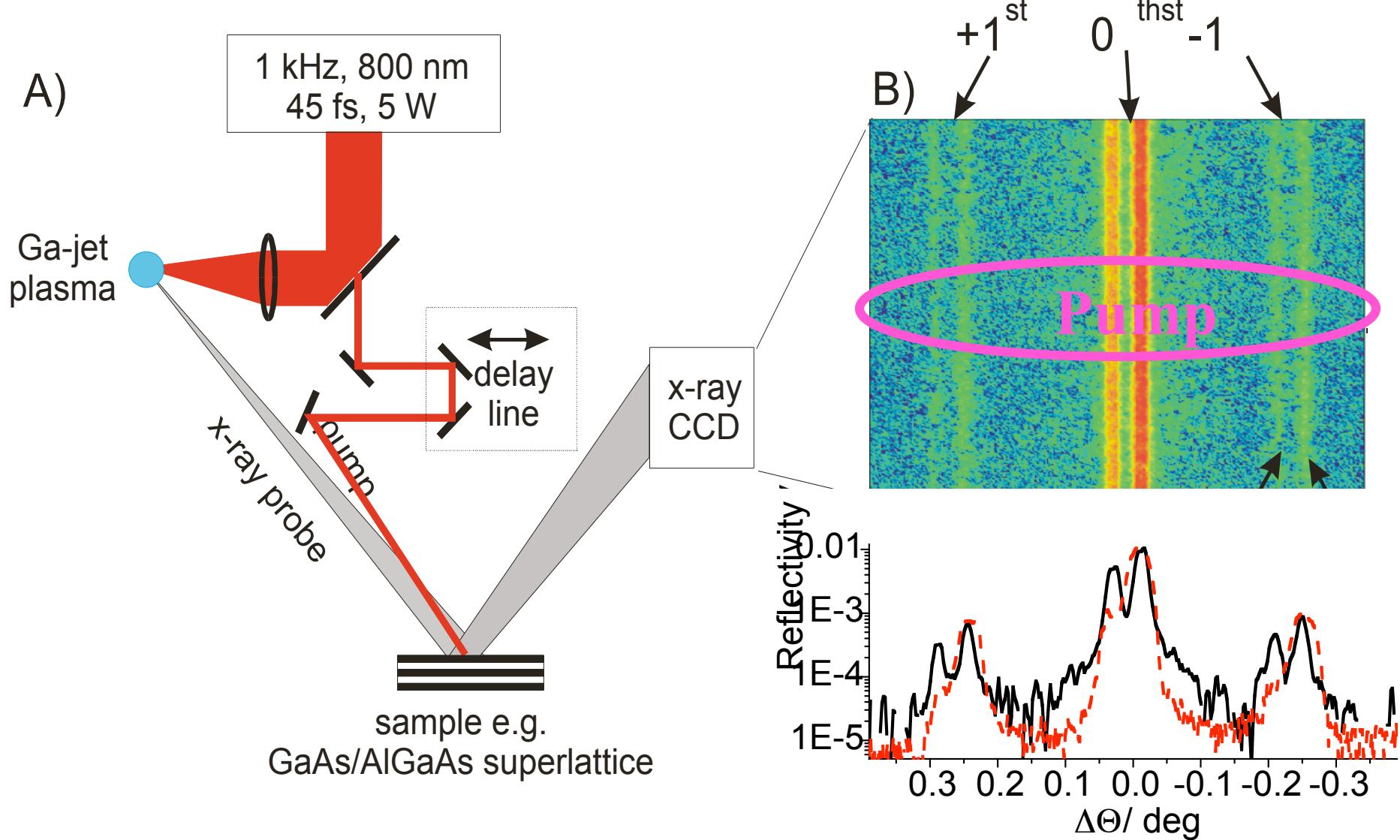
Simulation using Takagi-Taupin equations



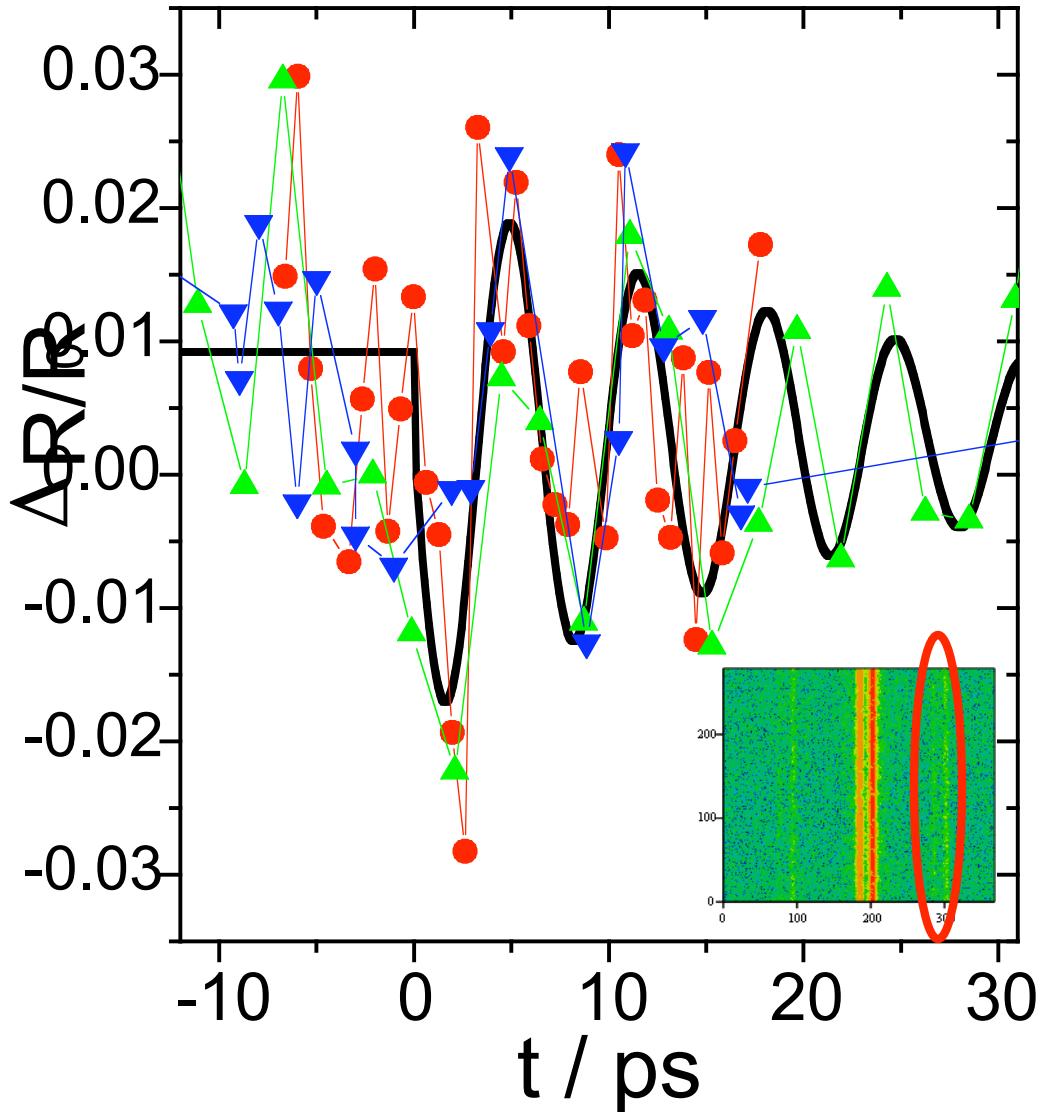
$$K' - K = G = G_L + n g_{SL}$$



Setup for Femtosecond X-Ray Diffraction

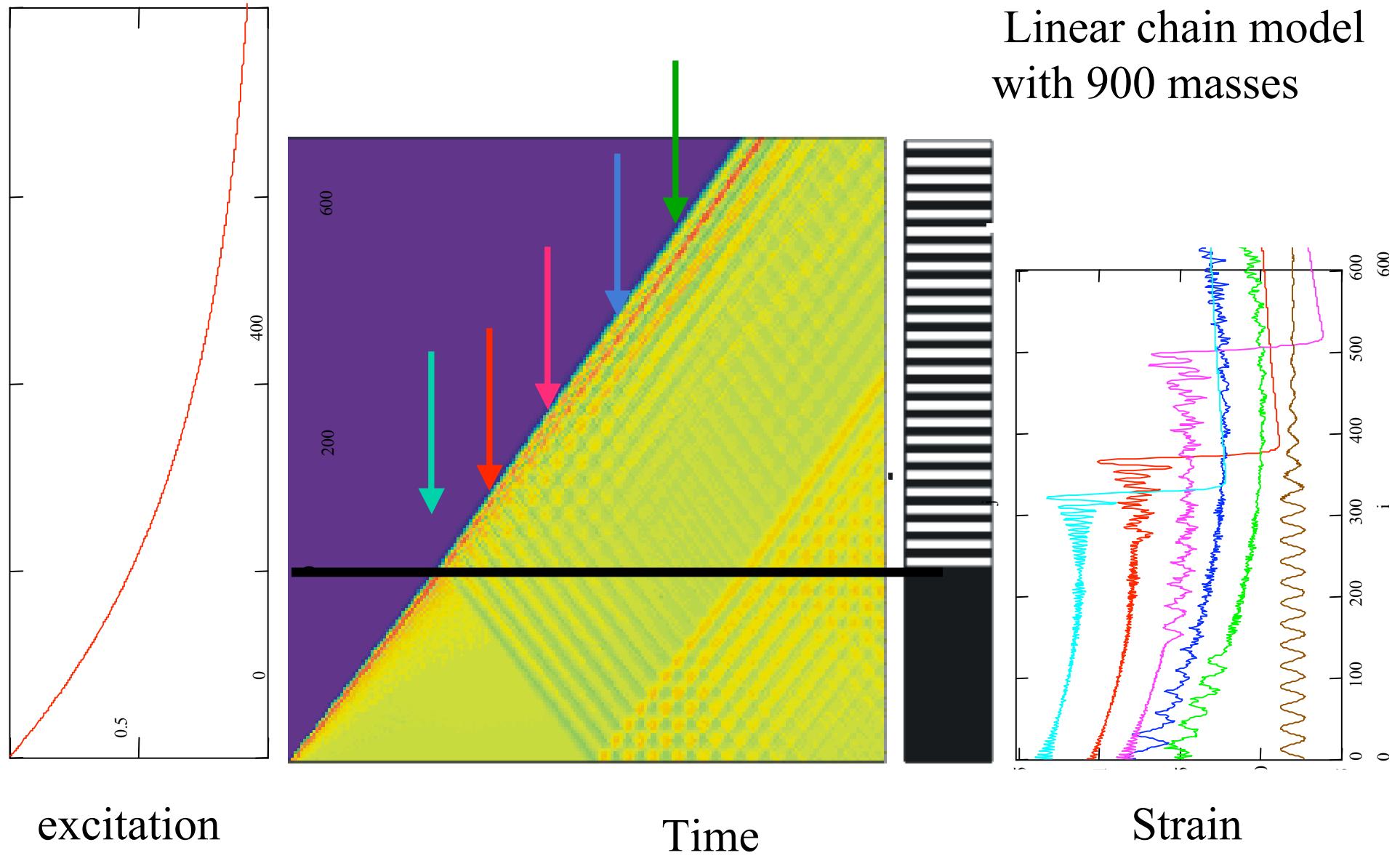


Femtosecond X-ray Diffraction from SL

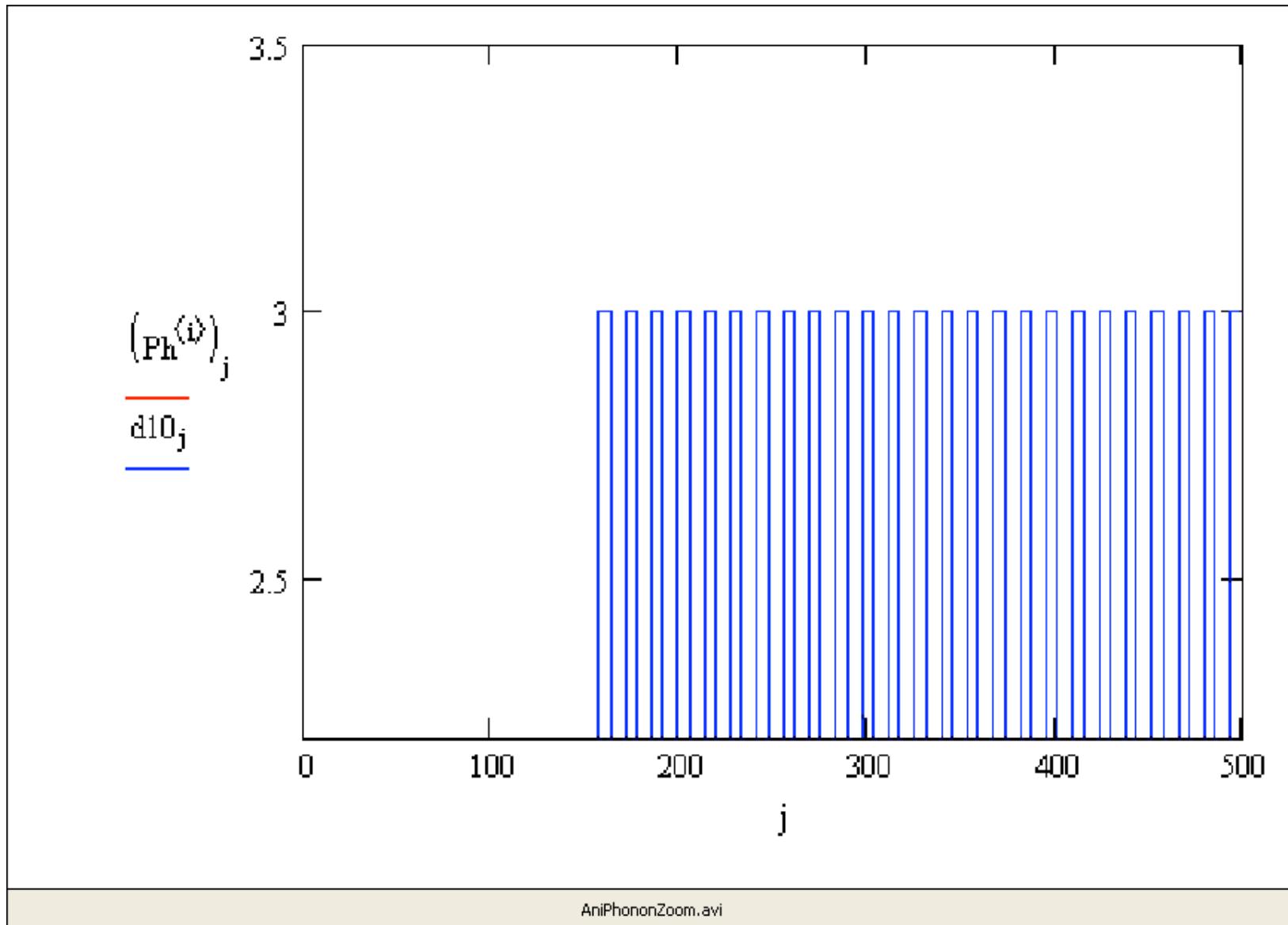


- first time-resolved diffraction from a superlattice
- sub-picometer structural changes with sub-picosecond time-resolution
- non-destructive
- coherent zone-folded acoustic phonon at zone-boundary: $T = 6.6 \text{ ps}$

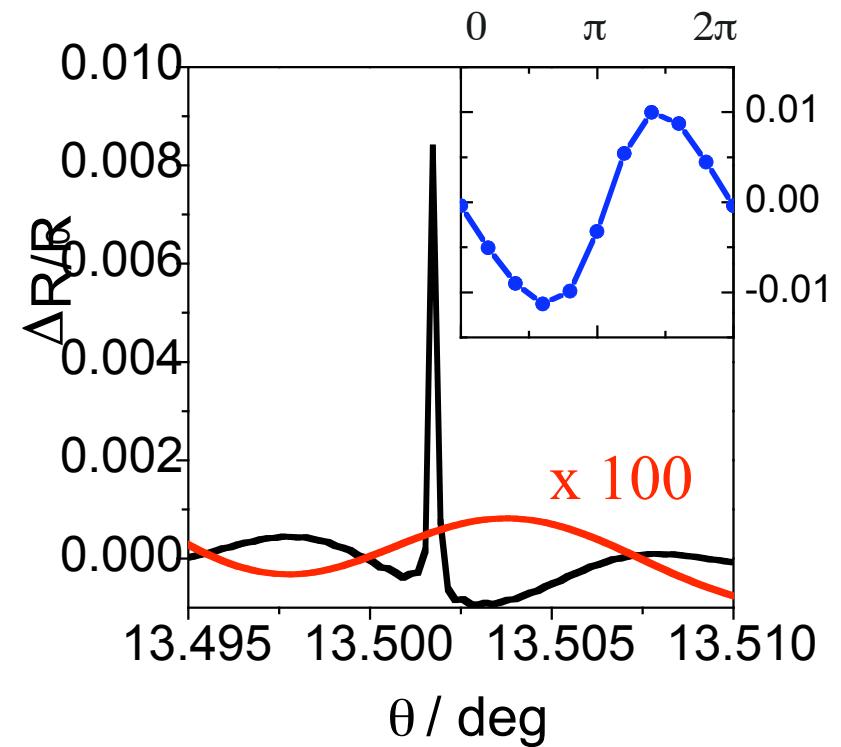
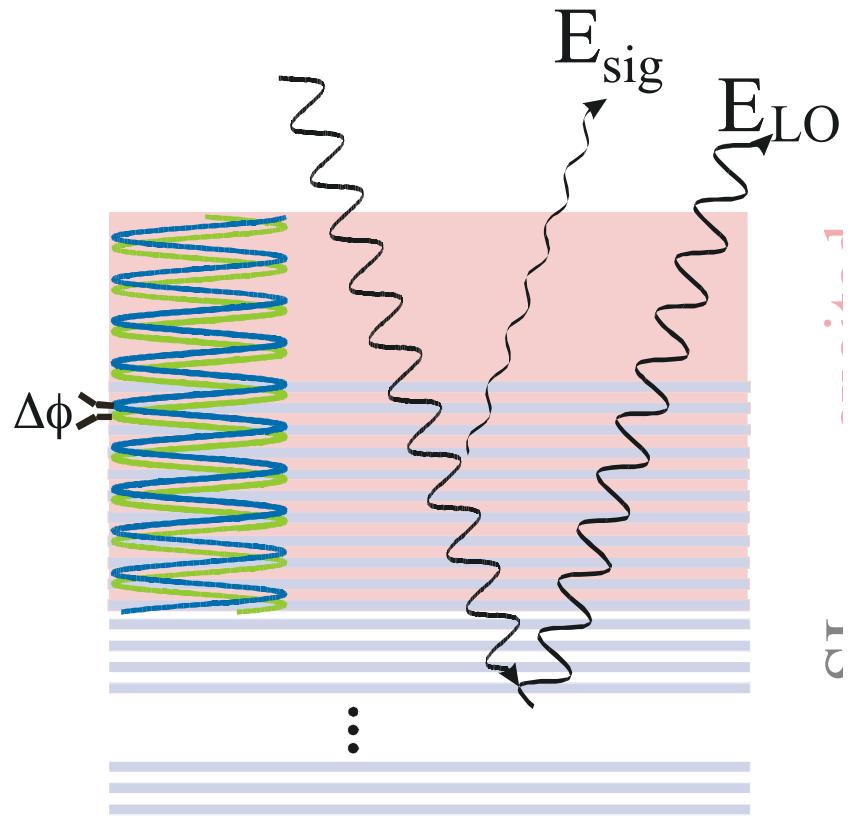
Simulation of Lattice Dynamics



Simulation of Lattice Dynamics



Homodyne-Detection of X-ray Diffraction



- Superlattice: strong reflection provides „local oscillator“ E_{LO}
- Excited nano-structure: weak reflection E_S
- Signal change linear and amplified
- $I = (E_{LO} + E_S)^2 \approx E_{LO}^2 + E_{LO}E_S$
- Sensitive to spatial phase of phonon

Interpretation

Phonon generation:

- High intensity => dense electron-hole plasma
- Wells and barriers equally excited

Phonon propagation:

- Sound-wave splits up at cap-layer / SL interface
- Confined phonon in cap-layer + modulated sound wave in SL

Detection:

- Static superlattice reflex: Local oscillator
- X-ray diffraction from phonon homodyne detected

Thanks

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D. H. Woo @ Korea Institute of Science and Technology, Seoul

D. S. Kim @ Seoul National University

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Future Directions

Ultrafast experiments (fs-XRD)

- Ultrafast phase-transitions (e.g. superconductor)
- THz excitation of polar phonon modes (SL)

Improvement of setup

- Focusing optics: Multilayer mirror, toroidal Bragg-reflector, single capillar total reflection
- Build several beamlines on the plasma-source
- Cryostat

Summary

- Generation of fs-x-ray pulses in laser-excited plasmas
- Experiment: Good S/N ratio and angular resolution

- Demonstration of femtosecond X-ray diffraction on nanostructures
- Non-destructive!
- Zone-boundary phonon (6.6 ps) excited at interface of cap-layer/SL
- Amplification by homodyning

